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Age Differences and Changes in Reaction Time: The Baltimore Longitudinal Study of Aging

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This study analyzed auditory reaction time (RT) data from 1,265 community-dwelling volunteers (833 males and 432 females) who ranged in age from 17 to 96. Cross-sectional analyses revealed slowing of simple (SRT) and relatively greater slowing of disjunctive (DRT; aka "go-no-go") reaction time across decades for both males and females. Repeated testing within participants (longitudinal analyses) over eight years showed consistent slowing and increased variability with age. Males were faster than females across age groups, RT tasks, and visits. Beginning at about age 20, RTs increased at a rate of approximately 0.5 msec/yr for SRT and 1.6 msec/yr for DRT. Errors also increased, making unlikely a tradeoff of accuracy for faster responses. The findings are consistent with the hypotheses that slowing of behavior is: (a) a continuous process over the adult life span; (b) characterized by age-associated increases in within-participant variability; (c) a direct function of task complexity and, presumably, the degree of mediation by higher regions in the central nervous system; and (d) greater in women than men.

MOST cross-sectional findings show age-related slowing of reaction time (RT) with increasing age (e.g., Era, Jokela, & Heikkinen, 1986; Harkins, Nowlin, Ramm, & Schroeder, 1974; Pierson & Montoye, 1958; Vrtunski, Patterson, & Hill, 1984; for reviews see Birren, Vercruyssen, & Fisher, 1990; Salthouse, 1985; Vercruyssen, 1991, 1993). Some studies of community-dwelling adults also have found consistent sex differences favoring males across all experimental conditions (e.g., Botwinick & Storandt, 1974; Harkins et al., 1974; Lahtela, Niemi, & Kuusela, 1985; Simon, 1967). Noble, Baker, and Jones (1964) report that, in an institutional setting, women were slightly faster than men in the 71–87 year age group. Others found men equally as fast as women, (e.g., Landauer, 1981; Landauer, Armstrong, & Digwood, 1980). These findings indicate a consistent pattern of increased reaction time with age in both men and women in a variety of tasks and a pattern of sex differences in RT that depends on the characteristics of the sample and the method.

Few longitudinal studies of RT have been published. While cross-sectional age differences were observed in the Duke Longitudinal Study (Wilkie, Eisdorfer, & Siegler, 1975), the longitudinal findings for both men and women indicated no age-related changes in total RT over six years in as much as a slower movement time was offset by faster decision times (Siegler, 1985). In the Bonn Longitudinal Study of Aging, the number of responses completed in a serial response task that became progressively more difficult decreased with age in men and women ranging in age from the 60s through the 70s. The change occurred over a 5-year period, and men were faster than women over several testings and in a comparable group of unpracticed participants (Mathey, 1976).

The Baltimore Longitudinal Study of Aging (BLSA), administered by the National Institute on Aging, has continually gathered longitudinal data on men since 1958 and on women since 1978 (Shock et al., 1984). Men and women are continuously added to the BLSA in such a way that will assure approximately equal numbers of male and female research participants with a similar number of years of observation. In 1991, the average number of years of observation was 16 for men and 7 for women. To date, more than 2,000 adult volunteers (17–104 yrs of age), mostly from the Baltimore-Washington metropolitan area, have been extensively tested at least once on a large battery of physiological and psychological measures, including detailed medical and personal history questionnaires. Simple (SRT) and disjunctive reaction time (DRT) tasks were introduced in 1973 to male participants and in 1978 to female participants, providing RT data on nearly 1,300 participants (over 5,000 visits). This is the first formal report on cross-sectional and longitudinal analyses of reaction time data from the BLSA.

METHOD

Participants. — Data from the first visits of 1,265 volunteers (833 male and 432 female) were used to conduct the cross-sectional analyses by age group (20–90 ± 5 yrs in decades). Longitudinal analyses were conducted using data aligned across participants to represent repeated testing of participants according to 2-year intervals between visits: 446

males and 134 females made at least three visits, and 264 males and 23 females made at least five. The actual intervals for some of the older men in the 1970s were 12 or 18 months for men in their 70s and 60s, respectively. Since 1978 the nominal interval between visits has been 2 years for all participants.

The participants comprise a self-recruited group who visit the National Institute on Aging (NIA) Gerontology Research Center every 2 years for 2.5-day testing sessions. They are neither a random sample nor a representative sample of the Baltimore population. The initial group of participants recruited their relatives, friends, and coworkers, who, in turn, recruited their relatives, friends, and coworkers, and so on. The result is a somewhat homogeneous group of participants from the upper-middle socioeconomic level who differ from the general population in that 90% are, by self-report, in good or excellent health on both their first and fifth visit, and are mostly married. About 73% of the men and 64% of the women had at least one college degree (Stone and Norris, 1966).

The distribution of educational level was wider for men than for women. The percentage distribution of education level for men/women was high school, 18/28; some college, 3/5; bachelor's, 32/39; master's, 23/21; PhD, 23/4; honorary doctorate, 2/1; other, 4/2. The men in general had a higher proportion of doctorates and honorary doctorates. Women had a high percentage of graduation from high school and some college.

Auditory reaction time tasks and procedure. — Participants were presented high (1000 Hz) and low (250 Hz) auditory tones through an overhead speaker at a level of 56 dBA. Prior to testing, the technician asked each participant if s/he could hear the tones comfortably. If the tones were not easily audible, the experimenter increased the stimulus intensity to 62 dBA and tried the tones again. The test was discontinued if the participant reported that the 62 dBA tones were not easily heard. The RT tasks were originally designed as part of a series of studies relating manual-response auditory RT to alpha wave events in electroencephalographic (EEG) recordings (e.g., Surwillo, 1961, 1963, 1964). Stimulus tones were presented for 3.0 sec during practice trials, and for 0.3 sec during actual testing (see Surwillo, 1963). In the simple reaction time (SRT) task, participants responded to both high and low tones by depressing a hand-held response button as quickly as possible. Participants were instructed to respond only to the high tone in the discrimination/disjunctive reaction time (DRT; aka "go-no-go") task. Stimuli were presented to all participants on all visits according to a single random order of variable interstimulus intervals (ISIs) ranging from 6 to 13 sec (see details in Chang, 1991). This particular range of ISIs was selected as being sufficient time to allow return of alpha components in the EEGs following a block (see Surwillo, 1966) of alpha caused by the previous RT trial (Quilter, 1992). One hundred twenty-two RT trials were presented in four blocks (approximately 5 min each). In SRT, the primary dependent measure was median correct RT for the final 20 trials of a total of 66 trials. In DRT, the corresponding measure was based on the last 26 DRT trials, 13 of which were high tones (correct response) and 13 were low pitched. Thirty unscored DRT trials were given prior to the scored DRT trials.

Participants were seated in a soundproof audiometry booth with their backs to the experimenter's viewing window. The booth was well lit and ventilated with a fan. The first 5-min RT test began after the appropriate stimulus intensity was determined. The experimenter gave the following instructions:

> In this first portion, I will administer either a high or low tone and you will respond by pushing this button as quickly as you can to all tones. Only one tone will be presented at a time and it could be high or low. There's no set pattern. The tones won't be long apart, but you won't know when one is coming. So you'll have to remain alert. This test will last about five minutes. Do you have any questions?

After this 5-min practice test (30 trials), the experimenter administered the same test a second time, presenting 36 trials. Responses to the last 20 were recorded in milliseconds (msec). The third 5-min test was DRT. The experimenter instructed the participant to respond only to the high tone, saying,

> . . . make your decision as fast as you can and press the button as fast as you can. Don't worry if you make a mistake, but try not to. No guessing. Make a fast, honest decision and press as quickly as you can to the high tone only . . .".

After about 5 minutes of practice on the DRT task (20 trials), the experimenter administered the fourth block (36 trials), recording RT raw data for the last 26 trials (13 low tones, 13 high tones).

With the exceptions mentioned earlier, each participant visited the Gerontology Research Center (GRC) about every two years (M = 2.18 yrs) for 2.5 days of extensive testing using a battery of physiological and psychological tests. From visit to visit across participants, the 20-min RT testing took place at different times during the 2.5-day period. Several participants had an irregular pattern of visits or visits in which RT tasks were not performed because of equipment failures, absence of the technician, or participants voluntarily skipping RT testing.

Other than difficulty in hearing the 62 dBA stimulus, there were no formal health-related exclusionary criteria for performance on the RT task. As is the case with all BLSA procedures, the RT tests were optional; therefore, participants occasionally elected to do only one of the two tasks, usually the SRT, or skip RT testing altogether for that particular visit. Such refusals were very infrequent and not systematically related to age of the participant.

According to the original design of the apparatus, reaction times longer than 800 msec were considered evidence that a response was not going to be made, so they were not recorded. Likewise, RTs shorter than 150 msec were considered to be due to anticipation and were not recorded. Errors of omission (i.e., failure to respond when appropriate within 800 msec) and commission (i.e., incorrect responses — those made to the low tones instead of the high in the DRT trials or those RT trials less than 150 msec) were expressed as a percentage of the RT trials analyzed. Unusually high error rates (as high as 100%) occurred in a few participants on a few visits; therefore, omitted from analyses were all visits in which RT errors were greater than 25%. Of 3,346 visits, 320 had an SRT or DRT task with greater than 25% errors (9.56%) and were omitted from analyses. Twenty-five percent was chosen to reduce spurious variability in errors (and possibly in RTs where tradeoffs might be present). This value represented the break point beneath which the number of participants excluded increased disproportionately (e.g., 30% cutoff removed approximately 240 participants). On rare occasions, first visit data were skipped if the task error rate was greater than 25% and the second visit was considered the first for analysis purposes. Also, many of the omitted sessions, due to errors being greater than 25%, occurred beyond the 8 years from the first visit, thereby affecting the results only in terms of linear regression estimates in the longitudinal analyses. The RT sampling window (>150 and <800 msec) was part of the data collection software designed by Surwillo (1961, 1963, 1964, 1966); and trials beyond these lower and upper limits were labeled as errors, and RTs were not saved. Thus, if the sampling window has any effect it would be in the direction of making more conservative the view of age-related slowing. Some young athletic males would be expected to produce some RTs of less than 150 msec in auditory simple RT tasks, but the BLSA SRT used longer than usual intertrial intervals, causing few cases to be faster than 150 msec. Across participants, errors of commission were near zero. Concerning the upper limit of the response window, some of the seven oldest females (85–94 yrs) had some of their responses occur after the 800 msec limit, resulting in such DRT trials being labeled as an error of omission and exclusion from analyses. Had the 800 msec limit not been imposed, the DRT for this group would have been slightly higher, and the errors and variance would have been slightly lower. Thus, the upper limit for data sampling causes a slightly conservative description of age-related slowing, but would not alter any of the findings from this research.

Data were collected from 1973 to 1991 using three generations of RT equipment. While objective tests comparing RTs on the separate pieces of equipment were not conducted, the expert engineers who designed and the technicians who maintained the equipment claim that these systems were virtually identical in terms of stimulus delivery, timing resolution, and experimental protocols. Preliminary analyses of RT means from the different generations of equipment were very similar, thereby supporting these claims. Once gathered, RT data were stored, along with all other participant information and test results, in a mainframe computer data base at the Gerontology Research Center.

Treatment of data. — Data analyses were conducted using microcomputers equipped with Intel 80386/7 and 80486 processors. All descriptive statistics and intercorrelations were conducted using DAS (Olofinboba & Vercruyssen, 1993), with univariate analysis of variance (ANOVA) conducted using BMDP Dynamic 386 (BMDP Statistical Software, 1990). All statistical contrasts were tested at the .05 level of significance with the more conservative Huynh-Feldt probabilities *(Hp)* presented along with conventional values *(p)* for all repeated measures ANOVAs. Post-hoc analyses were manually computed according to the Tukey *WSD* procedure (e.g., Vercruyssen & Hendrick, 1990).

Reaction time summary data (mean of means, mean of medians, mean of variance about the means, and mean percent errors) for SRT, DRT, and both tasks combined were analyzed according to a cross-sectional 2 × 8 (Sex × Age) between-groups ANOVA design for the first visit across participants. Analyses of visits 1–3 and 1–5 added a third factor of visits (repeated measures factor with levels of 3 and 5, respectively). When examining the interaction of SRT and DRT tasks, a fourth factor of task type (complexity) was added (with two levels, SRT and DRT). Age (decade) categories were 16–24, 25–34, 35–44, 45–54, 55–64, 65–74, 75–84, and 85+, with the midpoint of each interval being 20, 30, 40, 50, 60, 70, 80, and 90, respectively.

In order to get the most accurate representation of age-related changes within participants who had missing observations and to overcome problems of irregular visit schedules across participants, each participant's repeated measures data (means, medians, variances, and percent errors of SRT and DRT) were plotted according to time since first visit. In 2-year intervals (visits), RT measures were then extracted from each participant's data using both linear regression and linear spline curve-fit methods when the observed data did not coincide with the 2-year intervals. Figure 1 illustrates the data alignment procedures; it depicts hypothetical data points plotted, with data values extracted at 2-year intervals (note darkened vertical lines for yr 0–8) from the linear regression line (diagonal dashed line) and from the linear spline line (connecting solid lines). Both procedures resulted in equal numbers of data from all participants, and were particularly useful for estimating values for the few cases in which many years passed between visits. However, as illustrated, the values extracted could differ slightly, depending upon the estimation method. No extrap-

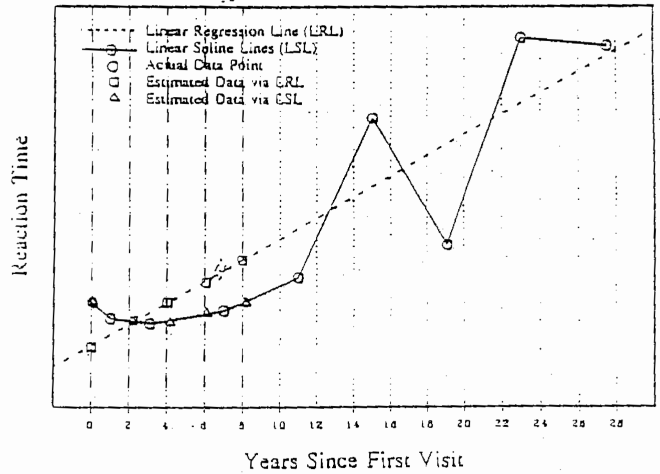

Figure 1. Sample set of reaction times for nine hypothetical visits (open circles) over 28 years illustrated by linear regression (diagonal dashed line), to show the overall trend within a participant, and by linear spline (solid connecting lines), to show visit-to-visit changes. Statistical analyses were conducted using data points extracted from both plotting procedures in 2-year intervals for years 0,2,4,6, and 8. Note that in this case the linear regression line shows slowing from year 0 to 8, but the linear spline line shows no change during this period.

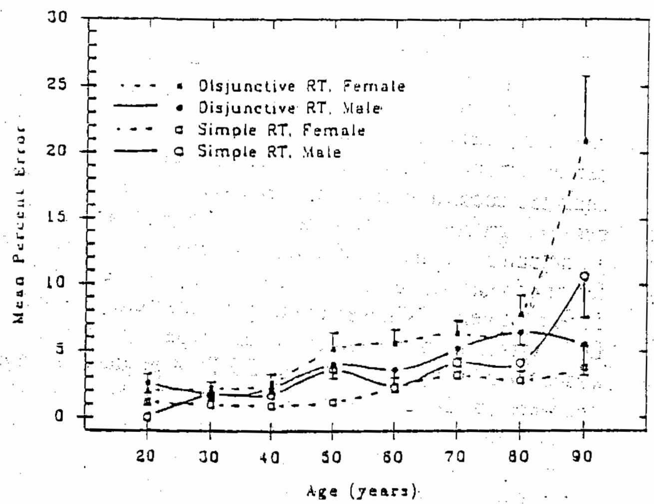

Figure 3. Mean percentage errors on visit one by age, sex, and task.

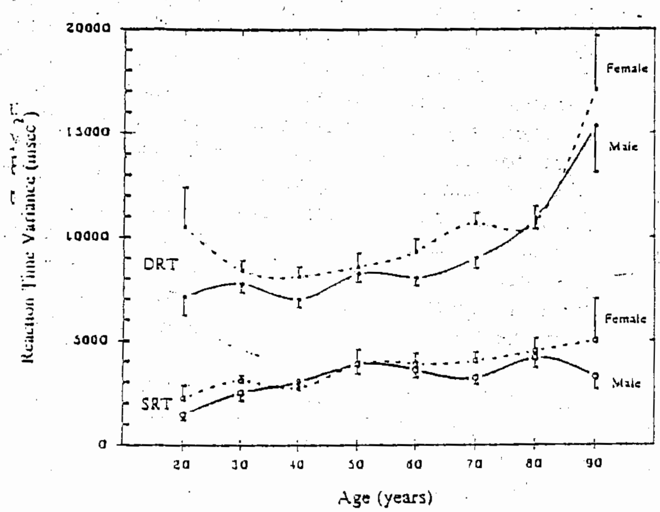

Figure 4. Mean variances on visit one by age, sex, and task type.

Disjunctive reaction time. — The DRT results are illustrated in Figures 2–4. The results of an ANOVA (see Table 1) on the means of median DRT performance revealed significant increases with age (Decades 2–9 = 377 ± 76, 378 ± 77, 396 ± 76, 412 ± 83, 415 ± 87, 446 ± 86, 460 ± 86, 479 ± 70) with males (M = 399.3 ± 82.3) consistently faster than females (M = 448.7 ± 86.0), but the Age × Sex interaction was not significant. Results obtained using mean RT data were similar to those obtained using medians.

As illustrated in Figure 3, percentage total errors on the DRT task increased significantly with age, males (M = 2.5 ± 5.4) were more accurate than females (M = 3.7 ± 6.5), and there was a significant Age × Sex interaction. For percentage errors of omission, males (M = 1.5 ± 3.1) made fewer errors than females (M = 2.1 ± 3.5), and errors increased continually from the second decade (M = 0.7 ± 1.8) to the ninth decade (M = 3.1 ± 4.1). For errors of commission, sex differences were not significant but errors were greater for the early decades (2nd = 7.8 ± 3.8, 3rd = 7.1 ± 4.3, 4th = 7.2 ± 4.2) than the later decades (5th = 5.6 ± 4.6, 6th = 6.0 ± 4.6, 7th = 5.5 ± 4.6, 8th = 5.5 ± 4.5, 9th = 5.8 ± 4.5).

Table 1. ANOVA Summary Table of Significant Cross-sectional Results (N = 1265)

Contrast Source	df	F	p-value	Eta^2
Simple Reaction Time				
Median correct				
Age	7, 1249	6.67	<.0001	.036
Sex	1, 1249	13.70	.0002	.010
Total errors				
Age	7, 1249	2.99	.0040	.016
Omission errors				
Age	7, 1242	22.89	.0067	.020
Variance				
Age	7, 1249	2.70	.0088	.012
Variance/Mean ratios				
Age	7, 1291	4.29	.0001	.185
Disjunctive RT				
Median correct				
Age	7, 1249	23.56	<.0001	.034
Sex	1, 1249	49.89	<.0001	.112
Total errors				
Age	7, 1249	7.35	<.0001	.038
Sex	1, 1249	17.89	<.0001	.013
Age × Sex	7, 1249	3.18	.0024	.017
Omission errors				
Age	7, 1242	6.02	<.0001	.030
Sex	1, 1242	7.36	.0067	.002
Commission errors				
Age	1, 1242	57.70	<.0001	.123
Variance				
Age	7, 1249	11.00	<.0001	.042
Sex	1, 1249	6.82	.0091	.005
Variance/Mean ratios				
Age	7, 1249	4.87	<.0001	.026
DRT & SRT Combined				
Median correct				
Age	7, 1249	19.20	<.0001	.030
Sex	1, 1249	41.93	<.0001	.015
Task	1, 1249	323.54	<.0001	.591
Age × Task	7, 1249	17.75	<.0001	.024
Sex × Task	1, 1249	33.25	<.0001	.050
Total errors				
Age	7, 1249	8.57	<.0001	.027
Sex	1, 1249	9.14	.0025	.004
Task	1, 1249	40.92	<.0001	.012
Age × Sex	7, 1249	2.15	.0366	.007
Age × Task	7, 1249	1.98	.0541	.004
Sex × Task	1, 1249	15.99	<.0001	.005
Age × Sex × Task	7, 1249	2.53	.0137	.005
Variance				
Age	7, 1249	9.25	<.0001	.030
Sex	1, 1249	6.71	.0097	.001
Task	1, 1249	490.29	<.0001	.385
Age × Task	7, 1249	4.72	<.0001	.025

Note. Data alignment to two-year intervals across participants via within-participant linear spline calculations.

Variance increased significantly with age (Decades 2–9

= 8747 ± 5557, 7997 ± 4963, 7402 ± 4315, 8328 ± 4644, 8376 ± 5043, 9735 ± 5412, 10840 ± 5558, 15795 ± 7339) with males (M = 8495.6 ± 5275.0) less variable than females (M = 9417.7 ± 5063.4), but the Age × Sex interaction was not significant. Within-participant variance/mean ratios increased in the 90-year-olds (Decades 2–9 = 22.6 ± 14.7, 20.5 ± 11.5, 18.4 ± 10.2, 20.0 ± 11.0, 21.9 ± 11.9, 23.7 ± 12.0, 33.7 ± 17.0). No other contrasts were significant.

DRT vs SRT. — Figure 2 illustrates the most important cross-sectional results for the means of median RTs, as a function of task type (see Table 1 for relevant ANOVA results). To examine age and sex differences, SRT and DRT data were analyzed as two levels of a single factor. This analysis was conducted more for verification of the task complexity hypothesis (e.g., Cerella, Poon, & Williams, 1980) than examination of decision processes via subtraction methods. Results of an ANOVA on the mean of median SRT and DRT revealed significant differences for Age, Sex, Task, Age × Task, and Sex × Task. The Age × Sex × Task interaction was nearly significant (p = .0511). No other contrasts were significant.

Similar results were obtained for percentage errors of the combined SRT and DRT data. Significant differences were obtained for Age, Sex, Task, Age × Sex, Sex × Task, and Age × Sex × Task. The Age × Task interaction was marginally significant (p = .0541). For variance, significant were the main effects of Age, Sex, and Task, as well as the Age × Task interaction.

Longitudinal Analyses

Three Visits Over Four Years

Simple reaction time. — After selecting only those participants who completed testing at least four years following their first visit, and sorting them into decades, ANOVAs (see Table 2) revealed significant age-related slowing of the mean of median SRTs where SRT went from 229.1 to 292.6 msec (see Figure 5). Males (M = 253.6 ± 46.4 msec) were also significantly faster than females (M = 273.5 ± 54.6). There was a significant increase in SRT with visits (Visit 1 M = 256.1 ± 15.0 msec, Visit 2 M 258.3 ± 18.5 msec, Visit 3 M = 260.5 ± 23.3 msec) and there was a significant Age × Sex interaction. No other interactions were significant.

Simple RT errors increased significantly with age (20's M = .06 ± .28, 30's M = 1.26 ± 2.71, 40's M = 1.59 ± 3.63, 50's M = 3.15 ± 6.54, 60's M = 1.93 ± 3.58, 70's M = 3.59 ± 5.04, 80's M = 4.68 ± 6.05). The only other significant contrasts for total errors, omission errors, or commission errors were in the spline analysis, where males (M = 1.8 ± 3.5) produced more omission errors than did females (M = 1.1 ± 2.8). Analyses of spline within participant variance revealed that only the visit main effect was significant (Visit 1 M = 3302.4 ± 4852.0, Visit 2 M = 3623.7 ± 4643.1, Visit 3 M = 3792.6 ± 4157.7).

Disjunctive reaction time. — Analysis of DRT data showed main effects for age (with increases per decade from 374.7 to 459.0 msec), sex (male M = 398.3 ± 70.4 msec, female M = 453.6 ± 71.0 msec), and visit (Visit 1 M = 406.1 ± 77.0 msec, Visit 2 M = 411.3 ± 71.8 msec, Visit 3 M = 416.4 ± 73.8 msec). There was an Age × Visit interaction such that, except for the 20-year-olds, DRTs increased from decade to decade and from visit to visit. Spline analyses also found a Sex × Visit interaction. No other interactions were significant. The same findings were obtained when analyzing means instead of medians.

Concerning analysis of DRT errors, results were similar to those found in analysis of the SRT errors. There were significant increases with age (20's M = 1.6 ± 4.3, 30's M = 2.1 ± 4.2, 40's M = 2.9 ± 5.0, 50's M = 3.9 ± 6.3, 60's M = 3.4 ± 5.5, 70's M = 5.0 ± 6.8, 80's M = 4.9 ± 7.3). Sex differences were close to being significant (male M = 3.2 ± 5.3, female M = 4.6 ± 7.0, regression p = .0574, spline p = .0558). No other main effects or interactions were significant.

However, closer examination of the spline analyses revealed opposite patterns for errors of omission and commission, thereby washing out an effect of total error. Errors of omission increased across decades (20s M = 0.7 ± 2.1 to 80s M = 2.1 ± 3.3), and males (M = 1.4 ± 2.77) made fewer errors than females (M = 2.1 ± 3.4). No other contrasts were significant. For errors of commission, no contrasts were significant except for age where, opposite of the trend for omission errors, increasing age caused a decrease in errors (20s M = 8.0 ± 3.3 to 80s M = 5.4 ± 4.3). Disjunctive RT variance differences were significant for age and sex (males M = 8165.0 ± 4682.2, females M = 9023.9 ± 4645.9).

DRT vs SRT. — Analyses of variance were performed on the median DRT and SRT spline data. Significant effects included: Sex (males M = 323.4 ± 95.2, females M = 360.5 ± 112.4), Task, Age × Task, Sex × Task, and Age × Sex × Task. No other contrasts were significant.

Corresponding significant results for errors included: Age, Age × Task, Age × Visit, Age × Sex × Task, Age × Task × Visit, and Age × Sex × Task × Visit. No other contrasts were significant.

Similarly, significant results for within-participant variance included: Task, Age × Task, Sex × Task, Age × Sex × Task, Age × Task × Visit, and Age × Sex × Task × Visit.

Five Visits Over Eight Years

Because of an insufficient number of participants per cell, ANOVAs on visits 1–5 involved only male participants in the 20–70 year age groups (total n = 279). Findings were similar for analyses of means as analyses of medians for both linear spline and linear regression estimation methods with all between-group differences and within-participant changes similar to the cross-sectional and longitudinal patterns; however, many of the ANOVA contrasts, specifically for the SRT task, failed to reach significance.

Discussion

The major findings of the present study are that SRT and DRT increase with age in men and women both when

Table 2. ANOVA Summary Table of Significant Longitudinal Results

Contrast Source	Method	df	F	p-value	Huynh-Feldt (Hp)	Eta²
Simple Reaction Time						
(Regress n = 616; Spline n = 580)						
Median correct						
Age	Regress	6, 602	3.50	.0021		.035
	Spline	6, 566	2.07	.0550		.015
Sex	Regress	1, 602	8.35	.0040		.014
	Spline	1, 566	6.53	.0109		.008
Visit	Regress	2, 1204	8.10	.0003	.0043	.013
	Spline	2, 1132	8.39	.0002	.0005	.003
Age × Sex	Regress	6, 602	2.37	.0283		.024
	Spline	6, 566	1.85	.0871		.014
Total errors						
Age	Regress	6, 602	3.47	.0022		.035
	Spline	6, 566	3.99	.0006		.025
Variance						
Visit	Regress	2, 1204	6.73	.0012	.0093	.011
	Spline	2, 1132	3.52	.0299	.0357	.001
Disjunctive Reaction Time						
(Regress n = 598; Spline n = 580)						
Median correct						
Age	Regress	6, 584	6.46	<.0001		.063
	Spline	6, 566	5.87	<.0001		.046
Sex	Regress	1, 584	28.52	<.0001		.049
	Spline	1, 566	26.92	<.0001		.035
Visit	Regress	2, 1168	5.54	.0040	.0183	.009
Age × Visit	Regress	12, 1168	2.66	.0016	.0141	.027
	Spline	12, 1132	1.72	.0569	.0682	<.001
Sex × Visit	Spline	2, 1132	3.53	.0297	.0362	<.001
Total errors						
Age	Regress	6, 584	2.40	.0268		.025
Sex	Regress	1, 584	3.62	.0574		.006
	Spline	1, 566	3.67	.0558		<.001
Omission errors						
Age	Regress	1, 565	2.09	.0526		<.001
Sex	Regress	1, 565	7.20	.0073		.009
Commission errors						
Age	Regress	1, 565	2.32	.0319		.002
Variance						
Age	Regress	6, 584	2.32	.0319		.024
	Spline	6, 566	2.17	.0444		.020
Sex	Spline	1, 566	4.29	.0388		.040
DRT & SRT Combined						
(Regress n = 598; Spline n = 580)						
Median correct						
Age	Regress	6, 581	4.63	.0001		.018
Sex	Regress	1, 581	22.95	<.0001		.015
	Spline	1, 566	9.25	.0024		.009
Task	Regress	1, 581	2135.04	<.0001		.403
	Spline	1, 566	116.89	<.0001		.017
Visit	Regress	2, 1162	12.18	<.0001	.0005	<.001
Age × Task	Regress	6, 581	6.04	<.0001		.007
	Spline	6, 566	17.98	<.0001		.016
Age × Visit	Regress	12, 1162	2.27	.0077	.0346	<.001
Sex × Task	Regress	1, 581	20.69	<.0001		.004
	Spline	1, 566	43.40	<.0001		.006
Age × Sex × Task	Spline	6, 566	20.67	<.0001		.019
Sex × Task × Visit	Regress	2, 1162	15.01	<.0001	.0001	<.001
Total errors						
Age	Regress	6, 581	3.56	<.0018		.020
	Spline	6, 566	4.69	<.0001		.012
Task	Regress	1, 581	18.27	<.0001		.009
Age × Task	Spline	6, 566	2.77	.0117		.007
Age × Visit	Spline	12, 1132	1.78	.0463		.005
Age × Sex × Task	Spline	6, 566	4.04	.0006		.006
Age × Task × Visit	Spline	12, 1132	2.12	.0138		.006
Age × Sex × Task × Visit	Spline	12, 1132	2.03	.0190		.006
Variance						
Task	Spline	1, 566	33.53	<.0001		.059
Visit	Spline	2, 1132	3.36	.0349	.0349	<.001
Age × Task	Spline	6, 566	3.65	.0014		.024
Sex × Task	Spline	1, 566	5.69	.0170		.035
Age × Sex × Task	Spline	6, 566	5.53	<.0001		.046
Age × Task × Visit	Spline	12, 1132	2.38	.0050	.0050	.008
Age × Sex × Task × Visit	Spline	12, 1132	2.08	.0158	.0158	.006

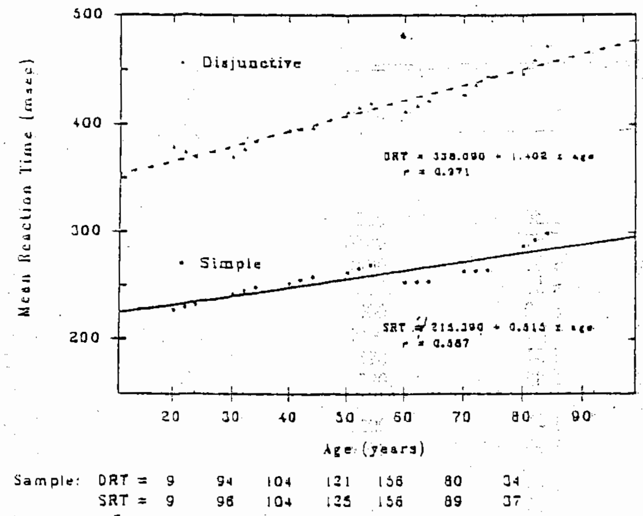

Figure 5. Mean of median reaction times for each of three visits (first visit plus 2 and 4 years) as a function of age and task.

indexed by age differences for first visit measurements of adults ranging in age from the 20s through the 90s and by age changes in RT measured serially in the same participants. The age-related increase in RT based on cross-sectional results is generally consistent with earlier results; the finding of age-related increases in serial observations of the same persons measured three to five times over 4- or 8-year periods is the first such report for SRT and DRT. Consistent across ages and visits, men were faster than women. Similarly, the number of errors and the within-participant variance of RT increase with age.

Errors. — In the cross-sectional results, total percentage errors made by both men and women increased with age in both SRT and DRT at the same time that mean RT and variances increased. The simultaneous increase in RT and errors in both tasks is inconsistent with the hypothesis that older participants trade faster response speed for greater accuracy. The fact that all participants received practice trials in each condition immediately prior to the collection of the data in that condition was included specifically to reduce the likelihood that older participants would be less adapted to the task demands than younger ones. While the results for the longitudinal analyses were less clear with respect to errors, the observed statistically significant trends for age or visit were consistent with the cross-sectional data: in no case did the number of errors decrease with age or later visits.

The positive relationship between errors and RT suggests that the estimate of age-related slowing in the present study is conservative, inasmuch that trials that had greater than 25% errors were removed from analysis. The average range of errors over age in the residual was 6–7%. The majority were errors of omission that increased with age, especially so in the older age groups on the DRT task. The number of errors of commission declined with age. The pattern of results is consistent with earlier results (e.g., Salthouse, 1985). In the more difficult DRT task, women made relatively more errors than men, largely due to the greater number made by women in the oldest age group. In the SRT condition there was no sex difference in the number of errors across age. While there is no obvious explanation of the sex differences, the fact that sex/gender differences are relatively more pronounced in the more difficult condition suggests that it is related to differences in strategy toward the decision task rather than in the basic physiological mechanisms that control RT.

Response variability. — Within-participant variance increased with age, both within participants and between groups, but these changes were proportional to changes in RT means. Similar results were obtained in the Duke study (Busse & Maddox, 1985). Although not tested, the notion of age-associated increases in internal or neural noise may help account for some of the changes in RT, errors, and variability (e.g., see Allen, 1991; Welford, 1981).

Cross-Sectional Age Differences

Consistent with previously reported literature, DRT is slower than SRT, and women are uniformly slower than men in all age groups, especially in older age groups. The interaction between age and RT tasks (complexity hypothesis) is consistent with some, but not all findings. The interaction may result from the very long interstimulus intervals (ISI) used in the present study or the fact that a disjunctive rather than choice reaction task was used or a combination. Using a variety of choice reaction time tasks, Fozard, Thomas, and Waugh (1976), Waugh, Fozard, Talland, and Erwin (1973), Waugh, Fozard, and Thomas (1978), and Waugh and Vyas (1980) all found that any unexpected change in a signal or a response resulted in a constant increase in response time in older participants over younger ones. However, the intertrial intervals were much shorter. Moreover, their choice reaction time task did not require an inhibition of response when an "incorrect" signal was presented, as in the case of DRT. While absolute differences between tasks increase with age, it is also important to note that this interaction disappears ($p < .05$) if differences are considered relative to initial levels (i.e., as a percentage of basal levels), suggesting that slowing is similar in the two tasks due to changes in the same processes.

While DRTs are usually faster than CRT, BLSA disjunctive RTs were slower than choice and disjunctive RTs reported in several other cross-sectional studies (e.g., Simon, 1967; Spirduso, 1975; Spirduso & Clifford, 1978). Most of this discrepancy may have been due to differences in ISI. For example, Spirduso (1975) used ISIs between 1.5 and 3.0 sec which were closer to the "optimal" ISI (Munro, 1951), whereas the BLSA ISIs ranged from 6 to 13 sec. Thus, having long ISIs in an RT study is likely to increase RT by requiring greater attentional demands, specifically preparedness and sustained attention.

Several other cross-sectional studies obtained results consistent with the BLSA cross-sectional age results from DRT (e.g., Botwinick & Storandt, 1974; Era et al., 1986; Fozard et al., 1976; Goldfarb, 1941; Harkins et al., 1974; Lahtela et al., 1985; Pierson & Montoye, 1958; Simon, 1967; Spirduso, 1975; Spirduso & Clifford, 1978; Szafran, 1951; Vrtunski et al., 1984; Waugh et al., 1973).

Sex Differences

Sex/gender differences favoring males have been found in many studies (e.g., Botwinick & Storandt, 1974; Harkins et al., 1974; Lahtela et al., 1985; Simon, 1967). Not all cross-sectional studies, however, observed such uniform results. For example, Noble et al. (1964) found males faster than females, except in a 71–87 year institutionalized age group where females responded faster than males. Landauer (1981) and Landauer et al. (1980) observed significantly faster decision times for females, and significantly faster movement times for males. Results of Lahtela et al.'s (1985) CRT task showed that men generally had higher error rates than women. In the BLSA, on the other hand, women had higher error rates than men on the DRT task.

Both the cross-sectional and longitudinal reaction time data from the Bonn Longitudinal Study of Aging indicated that practiced and unpracticed women had slower reaction times than men. Moreover, RT was positively correlated with intelligence test scores (Mathey, 1976), thus suggesting that RT is positively associated with intelligence, at least for the complex task employed in that study. Earlier it was noted that the distribution of educational attainment was not the same for male and female participants in the BLSA. Accordingly, the partial correlation between the first visit SRT and DRT data and educational attainment was calculated controlling for age. The partial correlations between level of education and SRT were .04 and .03 for women and men, respectively. The corresponding correlations for DRT were .07 and .02. Thus, sex differences in reaction time for men and women in the BLSA were not related to education levels when age differences were controlled.

Methodological Effects

Depending on whether data were estimated (aligned) using a linear regression or a linear spline technique, the results differed slightly. Using the linear regression method, results obtained were similar whether data were analyzed cross-sectionally, based on all participants' first visit, or longitudinally, according to repeated visits on each participant: (1) with older age comes a slowing of RT; (2) across ages, males are faster than females; (3) DRT is always slower than SRT; (4) the DRT-SRT difference increases with age; and (5) sex differences in SRT are small and unaffected by age, but sex differences in DRT are larger and increase with advancing age.

Using the linear spline method, the results obtained differed from the linear regression results depending upon whether data were analyzed cross-sectionally or longitudinally, especially when discussing age differences. Cross-sectional results can be summarized as follows: (1–5) above, and (6) errors within participant and variance for both SRT and DRT increase with age. Longitudinally, DRT slows with age over four years but the patterns of slowing for SRT, DRT, and decision time are not quite significant when analyses are based on visits over 8 years, presumably due to the increase in between-participant variance, decrease in sample size, and resulting decrease in statistical power. With approximately 400 participant visits added per year, future reanalyses of the updated data base should increase statistical power sufficiently to produce similar results for both data estimation procedures. Sex differences, however, were much stronger: males were still consistently faster than females. Results of analyses of within-participant variance showed that increases in variance due to age or to sex were not significant.

Within a session, DRT always followed SRT. Practice trials were given within each block of SRT and DRT before the scored trials in that condition were obtained, thereby providing an opportunity to adapt to the different task requirements of SRT and DRT. To the extent that fatigue effects may have occurred during the DRT trials, the reported differences between DRT and SRT may have been slightly overestimated.

Longitudinal Age Changes

Even though the Bonn Longitudinal Study of Aging (Mathey, 1976) employed a different type of CRT task, some of the results obtained were similar to those obtained in the BLSA. In the Bonn study, participants responded to a colored-light stimulus by pressing the button of the same color. The rate of presentation of the stimuli was gradually increased until the participant's error rate reached 50%. The total time taken to respond to a set number of stimuli was called the "circulation period." Bonn researchers found that the mean and standard deviation of the circulation periods increased with age. These changes were more dramatic between the 60–70 and the 70–80 year olds than between the 20–30 and the 60–70 year olds (Mathey, 1976).

Regarding sex differences, the BLSA results were consistent with those of the Bonn study. Though not as sizable as the age-related differences, significant sex differences were found in the Bonn study. Males were faster than females in all age groups, across all measurement points. The sex-related differences, like the age-related differences, became larger with age; sex differences were smallest in the 20–30 year old group, larger for the 60–70 year olds, and largest for the 70–80 year olds. In addition, women tended to have slightly higher standard deviations than men, but these differences were not observed in all samples at all measurement points (Mathey, 1976).

In discussing the Duke results, Shock (1985, p. 730) states that "[t]he inference, drawn from averages based on cross-sectional observations, that functions gradually decline over the entire adult life span was contradicted by the longitudinal finding that a substantial number of participants aged 65 and over showed no decline in health status or intellectual function, and that some actually showed improvement in health (Maddox & Douglass, 1973, 1974) over a number of years."

Results of longitudinal analyses of RT data from the Duke Longitudinal Studies were more consistent with the BLSA than with the Bonn study. Siegler (1985) found only small SRT and CRT changes across the first five examinations. "Cumulative frequency distributions developed for a subset of the subjects [using a procedure described by Fozard (1980)] indicated that the major longitudinal change was in the increased variance of performance across time" (Busse & Maddox, 1985, p. 82). Siegler (1985) reports analyses of RTs for five consecutive years within participants from 1955–1968 on a young-old group (65.5–76.9 yrs of age; *n*

= 46; called YO1), for similar tests on an old-old group (74.0–85.6 yrs of age; n = 26; called OO1), and for five consecutive years from 1970–1976 on returning members of the YO1 who qualified as old-old participants (78.4–85.6 yrs of age; n = 19; called OO2). Siegler (1985) briefly mentioned two RT results: first, averaging the YO1 and the OO2 cohorts across the first five testing sessions revealed significant decreases in RT and significant increases in MT with little change in overall response time across sessions. The meaning of this result is unclear.

While there are disadvantages to using longitudinal analysis in the study of aging (e.g., Damon, 1965; Shock, 1985), such as practice and period effects, recruitment of an "elite" participant pool, and participant drop-out, they are far outweighed by the advantages. Longitudinal research is capable of controlling birth-cohort effects, and identifying changes in individuals' performance as they age. In addition, its reliability increases with increased duration and frequency of testing. Cross-sectional analysis, on the other hand, can only identify differences between age groups. And, while practice and period effects are not a problem, the performance differences observed may be partly a result of factors other than age, such as cohort effects or selective survival (Damon, 1965; Shock, 1985).

Reports from many longitudinal studies (e.g., Bonn, Duke) mention a positive bias toward improved performance by those individuals who participate in such research over those in the general population, suggesting that longitudinal studies underestimate the actual decline in cognitive functions. No such trend was observed in the present study. Such differences may intensify as task demands become more stringent (see Siegler & Botwinick, 1979). Retest and sequential participation effects may be controlled by using designs with random sampling from the same cohorts, which may also reveal more severe declines in intellectual abilities (Siegler, 1985). Participant drop-out effects do not appear important in the BLSA data because first visit RTs across ages varied little when comparing data sets for all participants, visits 1–3 and visits 1–5, despite progressive decreases in sample size.

Restriction of Response Time Recorded

A technical point deserves comment. The high and low RT cutoff limits were restrictive in some cases. The data collection software was designed with a response window of 150 to 800 msec to accommodate EEG sampling. In retrospect, omitting data less than 150 msec is actually truncating the fast tails of simple RT distributions from certain participants, particularly young, physically fit males whose best efforts would be scored as errors. As a result of these analyses, in 1991 the data collection software was modified to make the lower limit 100 msec rather than 150 msec. On the other end of the RT distribution, some data from the slowest responders were omitted in cases where legitimate RT trials longer than 800 msec were labeled as errors and not analyzed. For example, a few older participants had average DRTs greater than 700 msec with error rates over the cutoff criteria of 25%, suggesting that this report is somewhat underrepresenting slower disjunctive RTs for some of the elderly. Thus, a slightly larger sampling window (e.g., 100–1200 msec) would have shown even greater differences between young adult SRTs and old adult DRTs (i.e., the Age × Task interaction).

Conclusions

This research quantifies, via cross-sectional and longitudinal experimental procedures, the degree to which reactive capacity declines with age as a function of sex and type of RT task. Corroborating the complexity hypothesis of aging, cross-sectional analyses showed that disjunctive RT increased more linearly with age (slope = 1.6 msec/yr) than did simple (slope = 0.5 msec/yr) RT (i.e., RT increased with task difficulty). Thus, in addition to a generalized slowing of central nervous system functions, aging disrupts decision-making processes and higher cortical functions. Longitudinal analyses also revealed slowing within participants for each age, in a manner slightly less consistent than but parallel to the results obtained in the cross-sectional analyses. The fact that males are consistently faster than females across the life span cannot be explained on the basis of education or general health, but there is no question RT slows in a predictable fashion with age for men and women and that this slowing may be exaggerated by increasing task difficulty or complexity.

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